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# Development of mungbean model (MungGro) and its application for climate change impact analysis in Bangladesh

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ABSTRACT

Mungbean (*Vigna radiate* L. Wilczek) is an important pulse crop for South Asian region. Its productivity is low and usually grown under water limited environments. Generally, irrigation at around flowering stage is provided if soil moisture is limiting. Its growth and yield is highly sensitive to fluctuations in climatic conditions, especially water-logging at any growth stage. Present study aimed at developing simple mungbean growth (MungGro) model, following the principles of SUCROS2 and the programme is written in Fortran Simulation Translator (FST). Water balance sub-routine has been undertaken along with G × E interaction, and the model was successfully calibrated and validated for growing environments of Bangladesh. Subsequently the model was utilized to evaluate the interaction effects of increased temperatures and carbon dioxide ($CO_2$) levels. Yield, in general, decreased with the rise in temperature, primarily due to reduction in growth duration and seed weight growth rate of the crop. Increased $CO_2$ levels compensated to some extent the deleterious effects of increased temperatures. Water-logging, especially at the beginning of the crop growth stage, had pronounced effect in reducing the grain yield drastically that was also reflected from the model. At present, we have calculated nitrogen (N) uptake and N fixation at the terminal stage of the crop. The model further needs to be improved by including N balance and insect-pest sub-routines.

## 1. Introduction

Mungbean is important pulse crop in Bangladesh and grows in many places under clear sunshine and low humidity conditions. Cloudy weather, incessant or heavy rainfall induces water-logging and cause insect pests and diseases problems. Such events might results in total crop failure or severe yield reduction. As temperature and carbon dioxide levels are likely to be increased in Bangladesh by 2050 and beyond (Biswas et al., 2017), gain yield of mungbean will be reduced greatly.

Legumes as a green manure provides N in rice-based cropping systems (Watanabe and Liu, 1992), which could be about 50–70 kg N/ha for the succeeding crops (Meelu and Rekhi, 1981). In general, higher grain yields are obtained from the succeeding crops after legumes (Singh et al., 1982). This increase in yield is attributed mainly to the increased N availability through N fixation and addition of crop residues to soil. As continuous cultivation of rice or wheat declined organic matter and N content in soils (Timsina et al., 2006), mungbean could be considered to enrich soils with nutrients (Bhuiyan, 2004).

Mungbean can be sown from 21 January to 30 March depending on location of the country and cropping patterns (Islam et al., 2016). Its growing as a summer crop can gave higher grain yields when sown on mid February to first week of March (Sarker et al., 2004; Miah et al., 2009). This crop is generally grown after T. Aman, mustard, wheat and potato. In general, mungbean growing areas are Barisal, Bogra, Chuadanga, Comilla, Dhaka, Dinajpur, Faridpur, Jenaidah, Jhalakathi, Jessore, Kushtia, Magura, Meherpur, Mymensingh, Pabna, Patuakhali, Rajshahi, Rangpur, Sherpur, Sylhet and Tangail districts of Bangladesh. It requires soil moisture for germination or post-sowing irrigation for stand establishment.

Conventional studies have showed responses of mungbean to elevated $CO_2$ levels (Uprety et al., 1996; Haque et al., 2005; Dey et al., 2017) and water-logging (Ullah, 2006); but no reports on higher temperature effects in this part of the world. To study combined effects of

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increased temperature, $CO_2$ levels along with water stress on mungbean growth and development for different regions of Bangladesh is not only time consuming but also very costly. Modeling can play an important role under such situations, although no suitable model for mungbean is available. However, van Keulen et al. (1992) developed crop growth model for water limited production environment. Our objectives were to develop a model (MungGro) for studying effects of elevated temperature, $CO_2$ levels and water stress on mungbean yield in Bangladesh and other South Asian countries.

## 2. Materials and methods

### 2.1. Development of mungbean (MungGro) model

Mungbean is an important crop of South Asia and widely grown in Bangladesh as fit-in crop in the major cropping systems. At present, no model dealing with this important pulse crop, so efforts were made to collate various plant processes behaviour from published literature (Haque et al., 2005; Ullah, 2006; Hayat et al., 2008; BARI, 2011-2117) in this region and transfer functions were developed to subsequently use in this model.

The programme is written in FST (Fortran Simulation Translator, Rappoldt and van Kraalingen, 1996) and the compiler used FST Win 4.12. It requires weather data, daily basis in specific format, for running of the model. Several global models viz. WOFOST, ORYZA, WTGROWS, and INFORCROP have been developed with FST Compiler and successfully used for yield estimates, natural resource management options and climate change studies. This compiler is easy to handle as it has specific in-built functions to conveniently write the programme.

The MungGro model was used to simulate yield with 0, 1, 2, and 3 °C rise in temperature under 380, 450, 550 and 650 ppm $CO_2$ levels having normal moisture and water-logged conditions. The model was used to see the effects of temperature rise by 1, 2, 3 and 4 °C on total growth duration (TD), grain filling duration (GFD) and seed weight growth rate (SWGR) at 380 ppm $CO_2$ and compared with no temperature rise.

## 3. Results and discussion

### 3.1. Description of mungbean growth (MungGro) model

Fig. 1 shows the key modules considered for development of MungGro model and Fig. 2 shows the major processes included in the development of this model, specifically for Bangladesh growing environments. Table 1 shows the list of State and Rate Variables used in the model development. Intermediate variables and Constants used in the model are described in the text, while describing the model. We now describe the various processes in details-

Initial conditions to be set before running the model are:

*NPL, no of plants per square meter = 35.*
*LA0, initial leaf area index = 0.0123*
*ZRTI, rooting depth at the beginning = 5.*
*WCLI1, volumetric moisture content, fraction of the first soil layer = 0.3*
*WCLI2, volumetric moisture content, fraction of the first soil layer = 0.3*
*WCLI3, volumetric moisture content, fraction of the first soil layer = 0.3*

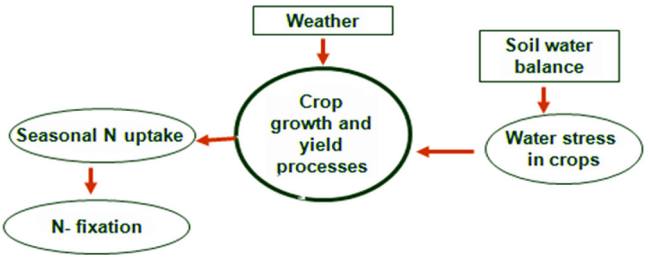


**Fig. 1.** Key modules of mungbean growth (MungGro) model.

In the dynamic mode, which is run on daily time step till the maturity of the crop, is described in the sections given below:

#### 3.1.1. Phenology

Phenology of mungbean is derived on the basis of growing degree days concept, with base temperature assumed as 8 °C. Development stage, normally described in the range 0–2, where 0 is the sowing, 1 refers to flower initiation and 2 is the harvest. Each cultivar has unique growing degree days for flower initiation and maturity. In the present context, BARI Mung-6 has been undertaken, which is the most common cultivar used by the farmers.

*DVS, development stage = INTGRL (0., DVR)*
*DVR, rate of development increase = INSW(DVS-1., AFGEN (DVRVT,DAVTMP), AFGEN (DVRRT, DAVTMP))*
*FUNCTION DVRVT = −10.,0., 0.,0., 8.,0.,40.,0.0498, for growing degree days requirement from emergence to flower initiation, 643 degree celcius–days as computed from historic datasets*

FUNCTION DVRRT = −10.,0., 0.,0., 8.,0.,40.,0.0542, for growing degree days requirement from flower initiation to maturity, 591 degree celcius - days as computed from historic datasets.

#### 3.1.2. Leaf $CO_2$ assimilation

Leaf $CO_2$ assimilation, expressed on per unit area basis and is computed in the model as described hereafter. It takes the potential value, crop/cultivar specific AMX, and corrected for the phenological stage, AMDVS; day time temperature dependence, AMTMP and $CO_2$ concentration increase effect, AMXCO2. The functional relationships have been developed from the secondary literature of field experiments conducted for the test crop under similar production environments.

*AMAX, leaf $CO_2$ assimilation, kg $CO_2$/ha/h = AMX * AMDVS * AMTMP*AMXCO2*
*AMX, crop and cultivar specific potential value = 15.*
*AMDVS, development stage dependence = AFGEN (AMDVST, DVS)*
*FUNCTION AMDVST = 0.0, 1.0, 1.6, 1.0, 2.0, 0.0*
*AMTMP, day time temperature, DDTMP dependence = AFGEN (AMTMPT, DDTMP)*
*FUNCTION AMTMPT = 0.,0., 8.,0., 20.,1., 35.,1., 40.,0.2, 45.,0.*
*AMXCO2, carbon dioxide (CO2, ppm) dependence = AFGEN (AMXCOT, CO2)*
*FUNCTION AMXCOT = 200., 0.85, 380., 1., 570., 1.2, 700., 1.25*

#### 3.1.3. Daily gross $CO_2$ assimilation

Canopy based assimilation was worked out from assimilation of leaf by the approach suggested by Goudriaan and van Laar (1978). A subroutine TOTASS has been included as part of the model, which divides the canopy in three layers for computing leaf $CO_2$ assimilation and integrated to work out the gross $CO_2$ assimilation.

*CALL TOTASS (DAY, LLAT, DTR, SCP, AMAX, EFF, KDF, LAI, DAYL, DTGA, DS0), sub-routine for computation of total assimilation through integration over the canopy; where inputs for driving the sub-routine are: DOY = day of year, EFF, initial light use efficiency in kg $CO_2$/ha leaf/h = 0.45, KDF, extinction coefficient for diffused light = 0.60, SCP, scattering coefficient of leaves = 0.20, LLAT, latitude of the site degrees = 23.4, LAI, leaf area index*
*The outputs coming from the sub-routine are: DAYL, astronomical day length, DTGA, daily total gross assimilation, kg $CO_2$/ha/day, DS0, daily extra terrestrial radiation*

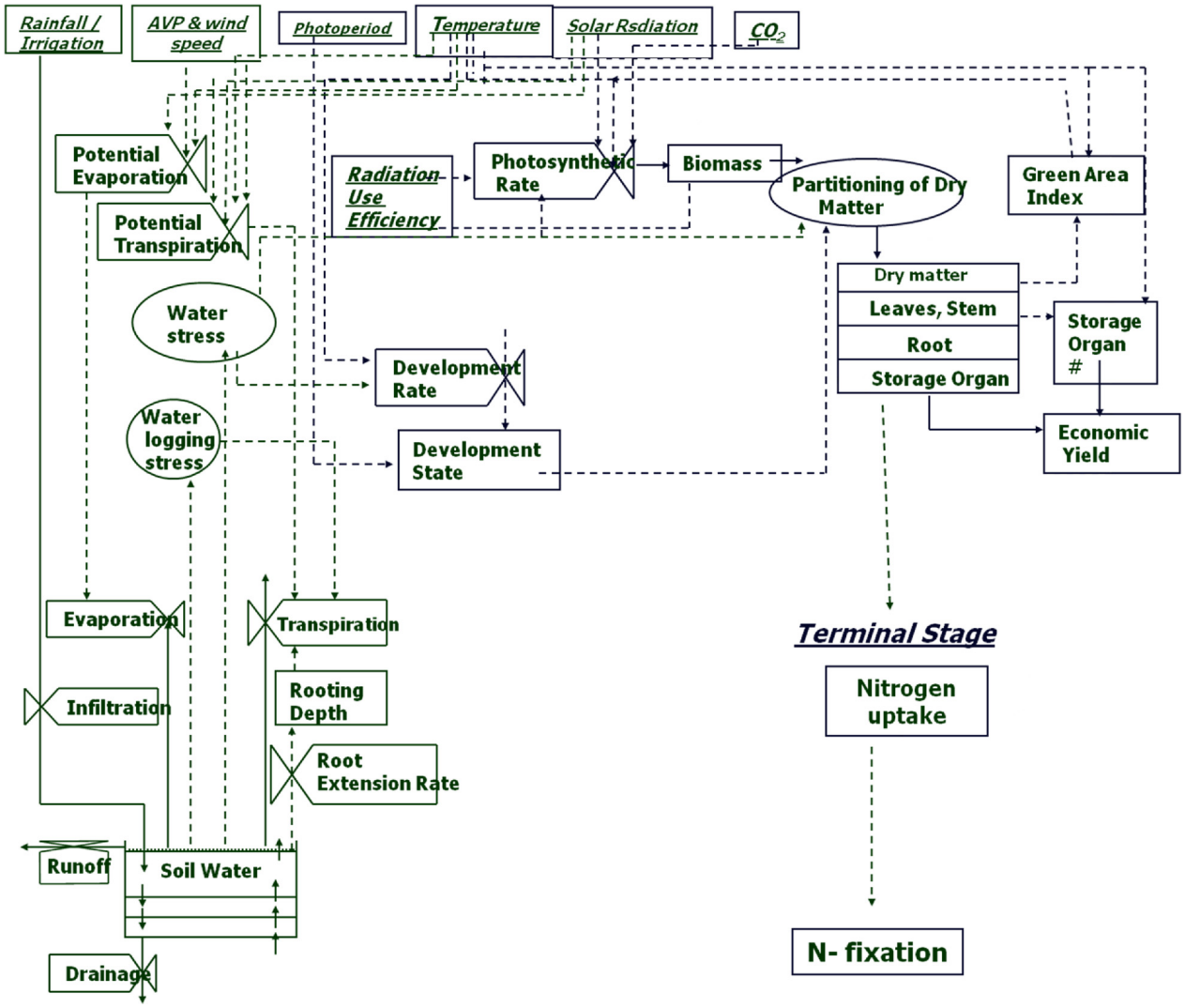


**Fig. 2.** Processes chart of mungbean growth (MungGro) model (AVP means atmospheric vapour pressure).

*3.1.4. Carbohydrate production*

GPHOT, carbohydrate production expressed in terms of kg $CH_2O$/ha/day = DTGA*PCEW*30./44, where PCEW refers to the water stress effect influencing the carbohydrate production.

*3.1.5. Maintenance*

Maintenance respiration as expressed in kg CH2O/ha/day, takes MAINTS, as computed from the biomass growth in terms of existing weights of the plant parts (WLVG, WST, WRT, WSO) potential respiration values, expressed in fraction of the weight components (MAINLV, MAINST, MAINRT and MAINSO)

*MAINT = MAINTS*TEFF*MNDVS*MAINTCO$_2$*
*MAINTS = MAINLV*WLVG + MAINST*WST + MAINRT*WRT + MAINSO*WSO*
*MAINLV = 0.03, MAINST = 0.015, MAINRT = 0.0 and, MAINSO = 0.01*

Temperatures increase the maintenance respiration and the dependence is computed through the relationship as given below:

*TEFF, temperature adjustment factor = Q10** ((DAVTMP − TREF)/10.), Q10 = 2.,*
*TREF = 30.*

Phenology adjustment factor, MNDVS is derived through ratio of green LAI to the total LAI (green plus dead leaves): *MNDVS = WLVG/NOTNUL (WLV)*

Although enhanced $CO_2$ concentration favours photosynthesis, but might cause increased maintenance respiration. Controlled experiments under elevated $CO_2$ conducted in Bangladesh were used to derive the adjustment factor for $CO_2$ elevated effect (MAINTCO2)

*MAINTCO2 = AFGEN (MAINCO2T, CO$_2$)*
*FUNCTION MAINCO2T = 300., 1., 380., 1., 570., 1.1, 700., 1.15*

*3.1.6. Dry matter partitioning*

Partitioning to various plant parts is crop/cultivar, phenology and biotic/abiotic stresses dependent. Presently BARI Mungbean-6 partitioning behaviour has been undertaken, but only water stress effect has been included. In the beginning root/shoot partitioning is carried out:

*FSH, fraction allocation to shoot = (FSHP*CPEW)/(1. + (CPEW-1.)*FSHP)*
*FRT, fraction allocation to roots = 1. − FSH*
*CPEW = Water stress effect*
*FSHP, allocation to shoots as related to development stage = AFGEN (FSHTB, DVS)*
*FUNCTION FSHTB = 0., 0.55, 1.4, 1., 2.,1.*

**Table 1**
List of major State and Rate Variables.

| State Variables |
|---|
| DVS = Development stage |
| LAI = leaf area index |
| W(RT, LV, ST, SO) = total (root, leaves, stem, storage organs) mass, kg/ha |
| TADRW = total above ground biomass, kg/ha |
| TDRW = Total biomass, kg/ha |
| HI = harvest index |
| WLLOSS(L, R, S, O) = weight loss of (leaves, roots, stem, storage organs), kg/ha |
| ZRT = rooting depth, mm |
| TPTRANS = Total potential transpiration, mm |
| TATRANS = Total actual transpiration, mm |
| TPEVAP = total potential soil evaporation, mm |
| TAEVAP = total actual soil evaporation, mm |
| TOTN(Y, S, AGBM, RT) = N uptake by (seeds, stover, above ground biomass, root), kg/ha |
| TNFIX = total N fixation through Rhizobium, kg/ha |
| **Rate Variables** |
| DVR = Rate of development stage increase |
| AMAX = Leaf $CO_2$ assimilation, kg $CO_2$/ha/h |
| DS0 = Daily extra terrestrial radiation, KJ/ha/day |
| GPHOT = Carbohydrate production, kg $CH_2O$/ha/d |
| MAINT = Maintenance respiration as expressed in kg CH2O/ha/d |
| G (TW, RT, LV, ST, SO) = Gain in (biomass, root, leaves, stem and storage organs), kg/ha/day |
| DLAI = Death in LAI, per day |
| WLLOSS (L, R, S, O) = Weight loss of (leaves, roots, stem, storage organs) in kg/ha/day |
| PENMAN = Reference evapo-transpiration mm/day |
| EVAPR = Radiation balance term of PENMAN |
| DRYP = Air drying powerterm of PENMAN |
| WLFL(1,2,3,4) = Downward movement of water (surface, first layer, second layer, third layer), mm/day |
| WLFL(5,6,7,8) = Upward movement of water (in third layer, second layer, first layer, surface layer), mm/day |
| EZRT = Rooting depth increment |
| PTRANS = Potential transpiration rate, mm/day |
| TRWL(1–3) = Water withdrawal from layer (1–3), mm/day |
| ATRANS = Actual transpiration, mm/day |
| PEVAP = Potential evaporation from soil, mm/day |
| AEVAP = Actual evaporation from soil, mm/day |
| EVSW(1–3) = Actual soil evaporation contribution from layer (1–3), mm/day |

Partitioning of the shoot mass to various plant parts is primarily development stage dependent and the relationships are given below:

*FLV, fraction of shoot portion allocated to leaves = AFGEN (FLVTB, DVS)*
*FUNCTION*
*FLVTB = 0.00,0.65,1.,0.65,1.15,0.45,1.45,0.06,1.6,0.04,2.,0.*
*FST, fraction of shoot portion allocated to stem = AFGEN (FSTTB, DVS)*
*FUNCTION*
*FSTTB = 0.00,0.35,1.,0.35,1.15,0.48,1.45,0.39,1.6,0.16,2.,0.*
*FSO, fraction of shoot portion allocated to storage organs = INSW (DVS-1., 0., 1. − FLV − FST)*

### 3.1.7. Growth of plant organs and translocation

For computation of the gains in total biomass, assimilates (in terms of CH2O) available for daily growth, maintenance respiration and translocation are required. Since the values to convert in kg biomass/ha/day, the conversion factors for various plant parts are needed, which have been taken from standard literature, as indicated below:

*ASRQRT = 1.389, ASRQLV = 1.389, ASRQST = 1.449 and ASRQSO = 1.389*

Translocation of C from stem after a specific stage for the partitioning process, TRANSL, which generally occurs after flowering, is computed as below:

*TRANSL = INSW (DVS-1., 0., WST*DVR*FRTRL)*
*where FRTRL = 0.20*

Gains in biomass, on daily time step, is computed as

*GTW = (GPHOT − MAINT + 0.947*TRANSL*CFST*30./12.)/ASRQ*
*ASRQ = FSH*(ASRQLV*FLV + ASRQST*FST + ASRQSO*FSO) + ASRQRT*FRT*

Gain in biomass is partitioned to various plant parts on the basis of equations as described below:

*GRT, growth rate of roots = FRT * GTW - WLLOSSR*
*GLV, growth rate of leaves = FLV * FSH * GTW − WLLOSSL*
*GST, growth rate of stems = FST * FSH * GTW − TRANSL − WLLOSSS*
*GSO, growth rate of storage organs = AMAX1 (0., FSO * FSH * GTW − WLLOSSO)*

In these equations, WOLOSS-R, L, S, O have been introduced to include water-logging effects as mungbean is very sensitive to it, more pronounced in the earlier stages. Water-logging effect will be discussed in the later stages of model description.

### 3.1.8. Leaf development

From the daily gains in leaf weight, LAI gain, GLAI, is computed by using specific leaf area, SLA which is development stage dependent. In the beginning, SLA values are generally higher and decrease as the growth progress. Senescence of leaf, in particular after flowering, has to be included through death in LAI, DLAI. The model is very sensitive in putting the initial LAI value, LA0 and also on the relative leaf area growth and death rates (RGRL, RDR respectively). The values of these important parameters are derived from the secondary literature for this region (Mondal et al., 2012; Rana et al., 2012; Uddin et al., 2013).

*RGRL, relative growth rate of leaves = 0.0085*
*SLA, specific leaf area = AFGEN (SLATB, DVS)*
*FUNCTION SLATB = 0., 0.0029, 1., 0.0029, 2., 0.0013*
*DLAI = LAI * RDR*
*RDR, relative death rate = AFGEN (RDRTB, DVS)*
*FUNCTION RDRTB = 0., 0., 1., 0., 1.45, 0.01, 2., 0.03*
*DLV, weight of dead leaves, kg/ha = WLVG * DLAI/LAI*

Sub-routine to compute gain in leaf area index (GLAI)

*CALL GLA (DAY, DOYEM, DTEFF, DVS, NPL, LA0, RGRL, DELT, SLA, LAI, GLV, GLAI)*
*TMP1 = INTGRL (ZERO, GLAI)*
*TLAI = TMP1*
*TMP3 = GLAI-DLAI*
*TMP2 = INTGRL (ZERO, TMP3)*
*LAI = TMP2*

### 3.1.9. Dry matter production

On the basis of above calculations, biomass production (also including various plant parts) and harvest index (HI) are computed, as described below:

*WRT, total root mass, kg/ha = INTGRL (WRTI, GRT)*
*TMP4 = GLV (daily gains in leaf weight, kg/ha) - DLV (death rate in leaf weight)*
*WLVG, total green leaves biomass kg/ha = INTGRL (WLVI, TMP4)*
*WLVD, total dead leaves biomass kg/ha = INTGR L (ZERO, DLV)*
*WST, total stem biomass kg/ha = INTGRL (WSTI, GST)*

*WSO, total storage organs biomass kg/ha = INTGRL (ZERO, GSO)*
*WLV, total weight of leaves, kg/ha = WLVG + WLVD*
*TADRW, total above ground biomass, kg/ha = WLV + WST + WSO*
*TDRW, total biomass, kg/ha = TADRW + WRT*
*HI, harvest index = WSO/TADRW*

### 3.1.10. Water-logging stress effect

Mungbean is sensitive to water-logging and the crop is damaged if water stagnation persists for 24 h. If water-logging occurs in post-flowering stage, it may cause reduction in yield by around 20% per day event occurrence (Ullah, 2006).

*WLOGIN, water-logging reduction factor in various plant parts in the initial stages of crop growth till DS < 0.8 = 0.9*
*WLOGLT, water-logging reduction factor in various plant parts in the later stages of crop growth, DS > 0.8 till harvest = 0.2*
*REDWLOG, reduction factor switch = INSW (DVS-0.8, WLOGIN, WLOGLT)*
*WLSEFF, condition of occurrence of water logging = INSW (WLFL8-5., 0., REDWLOG), WLFL8 is the amount of water staying on the soil surface after recharging the root zone till saturation*
*WLLOSSL, weight loss of leaves kg/ha = WLV*WLSEFF*
*WLLOSSR, weight loss of roots kg/ha = WRT*WLSEFF*
*WLLOSSS, weight loss of stems kg/ha = WST*WLSEFF*
*WLLOSSO, weight loss of storage organs kg/ha = WSO*WLSEFF*

### 3.1.11. Weather data

Weather data is read from external file on daily time step, and the parameters required are maximum and minimum temperatures in degree celcius, solar radiation in KJ/$m^2$/day, vapour pressure in kPa, wind speed in m/sec, rainfall in mm. The format for weather file is adopted from FST compiler requirements. Brief description of the weather parameters and derived weather parameters are given as below:

WEATHER WTRDIR = 'C:WEATHER';CNTR = 'GAZI';ISTN = 1; IYEAR = 2001

*DTR, solar radiation = RDD*
*DTMAX, maximum temperature = TMMX + COTEMP*
*DTMIN, minimum temperature = TMMN + COTEMP*
*DAVTMP, average temperature = 0.5 * (DTMAX + DTMIN)*
*DDTMP, day time average temperature = DTMAX − 0.25 * (DTMAX - DTMIN)*
*COTEMP, temperature rise switch = 0. (may have value according to temperature rise scenario)*
*DTEFF, effective temperature = AMAX1 (0., DAVTMP - TBASE)*
*TBASE, base temperature below which the activity does not take place = 8.*
*AVP, actual vapour pressure = VP*
*WDS, wind speed = WN*
*RRAIN, rainfall = RAIN*
*TRAIN, cumulative rainfall = INTGRL (ZERO, RRAIN)*
*$CO_2$, carbon dioxide concentration in ppm = 380.*

### 3.1.12. Penman-Monteith combination equation

Reference evapo-transpiration (i.e. maximum ET) is a function of crop/cultivar, phenological stage and weather condition, and in this model the method, as suggested by Penman-Monteith, has been followed. It basically employs radiation balance and air drying power components. The brief description of the process is given below:

*PENMAN, reference evapo-transpiration mm/day = EVAPR + EVAPD*
*EVAPR, radiation balance term = (1./LHVAP)*(SLOPE/(SLOPE + PSYCH)) * NRAD*
*SLOPE, temperature verses saturated vapour pressure = 4158.6 * SVP / (DAVTMP + 239.)**2*
*SVP, saturated vapour pressure as derived from average temperature = 6.11 * EXP (17.4 * DAVTMP / (DAVTMP + 239.))*
*LHVAP, latent heat of evaporation = 2.4E6*
*PSYCH, psychrometeric constant = 0.67*
*NRAD, net radiation = INCOM-RLWN*
*INCOM, incoming solar radiation = (1. − ALB)* DTR, solar radiation*
*ALB, albedo = ALBS*EXP (−0.5*LAI) + 0.25*(1. − EXP (−0.5*LAI))*
*ALBS, albedo of soil surface = 0.25 * (1. − 0.5*WCL1/WCST1)*
*RLWN, outgoing long wave radiation = BBRAD*FVAP*FCLEAR* 86400.*CFAC*
*CFAC = 0.1*
*BBRAD, black body radiation = BOLTZM * (DAVTMP + 273.)**4*
*BOLTZM, Boltzmann's constant = 5.668E-8*
*FVAP = 0.56 - 0.079*SQRT (AVP)*
*FCLEAR, cloud clear fraction for solar radiation estimation = 0.1 + 0.9*CLEAR*
*CLEAR = LIMIT (0., 1., ((DTR/DS0) − A)/B)*
*Angstrom Constants- A = 0.32, B = 0.45*
*WDF, wind factor = 0.263 * (1.0 + 0.54 * WDS) * PSYCH*
*DRYP, air drying power for RET estimates = (SVP-AVP) * WDF*
*TPENM, cumulative RET = INTGRL (ZERO, PENMAN)*
*TEVAPR = INTGRL (ZERO, EVAPR)*
*TEVAPD = INTGRL (ZERO, EVAPD)*

Evapo-transpiration can be computed from pan evaporation by incorporating pan coefficient and crop coefficients, which is relatively easier and presently we are attempting to develop module for ET estimates for important crops of this region.

### 3.1.13. Soil water balance

Soil water balance sub-routine is based on the approach in SUCROS2 as followed by van Keulen et al. (1992). In this paper, brief explanation of the procedure followed for soil water balance components is described. The root zone is divided in three layers, with total soil depth assumed up to 60 cm, as roots of mungbean crop are confined up to this depth.

*TKL1 = 200., TKL2 = 200., TKL3 = 200.*
*TKLT, total profile thickness in mm = TKL1 + TKL2 + TKL3*

Rain water, as intercepted by the canopy is given as under,

*AINTC = AMIN1 (RRAIN, INTC*LAI)*
*INTC = 0.25*

Runoff is estimated as per the procedure given below:

*RNOFF = AMAX1 (0., ABC*(RRAIN - AINTC - 10.))*
*ABC = .15*

Redistribution of water, received in terms of rainfall and irrigation, is done within 24 h and the procedure is described as below:

### 3.1.14. Downward movement of water after rainfall/irrigation and after recharging the soil layers to field capacity

*WLFL1, water available for surface entry, in mm = AMAX1 (0., RRAIN - AINTC - RNOFF + IRRIG)*
*WLFL2, water available for downward entry for second layer in mm = AMAX1 (0., WLFL1 - (WCFC1*TKL1 - WL1))*
*WLFL3, water available for downward entry for third layer in mm = AMAX1 (0., WLFL2 - (WCFC2*TKL2 - WL2))*
*WLFL4, water available for drainage out of the root zone in mm = AMAX1 (0., WLFL3-(WCFC3*TKL3-WL3))*
*DRAIN, drained water out of root zone in mm = AMIN1 (DRATE,*

*WLFL4)*
*DRATE, drainage rate in mm/day = 20.0 (the value may change depending on the soil type)*

*3.1.15. Water available for upward movement after drainage/recharging a layer to saturation*

*WLFL5, water available for saturating layer-3 and balance as upward movement in mm = INSW ((DRATE - WLFL4), (WLFL4 - DRATE), 0.)*
*WLFL6, water available for saturating layer-2 and balance as upward movement in mm = INSW ((DRATE − WLFL4), AMAX1 (0., WLFL5 − (WCST3*TKL3 - WL3)), 0.)*
*WLFL7, water available for saturating layer-1 and balance as upward movement in mm = INSW ((DRATE-WLFL4), AMAX1 (0., WLFL6-(WCST2*TKL2-WL2)), 0.)*
*WLFL8, standing water after saturating the root zone in*
*mm = INSW ((DRATE-WLFL4) AMAX1(0., WLFL7-(WCST1*TKL1-WL1)), 0.)*

*3.1.16. Water stress effect*

Soil water availability plays a key role in deciding the actual water withdrawal and thereby defining how far the actual transpiration is away from the potential transpiration. If the moisture availability is not appropriate, the phenology and other key plant processes would be hampered and reduction in growth and yield of crops would take place. The following steps describe that how water stress effect in various root zone layers is estimated.

*RWCL1, relative water content of first soil layer = (WCL1 − WCWP1)/(WCFC1 − WCWP1)*
*RWCL2, relative water content of second soil layer = (WCL2 − WCWP2)/(WCFC2 − WCWP2)*
*RWCL3, relative water content of third soil layer = (WCL3 − WCWP3)/(WCFC3 − WCWP3)*

On the basis of relative water content, water stress effect for layers is derived:

*WSE1 = AFGEN (WSET, RWCL1)*
*WSE2 = AFGEN (WSET, RWCL2)*
*WSE3 = AFGEN (WSET, RWCL3)*
*FUNCTION WSET = −1., 0., 0., 0., 0.4, 1., 1., 1.*

The function WSET clearly indicate that if RWCL1–3 is greater than 0.4, the availability of water to roots is not affected and the water uptake could be as per the demand set for that layer by the atmosphere.

*3.1.17. Soil moisture constants*

Four soil moisture constants play key role in moisture retention and for water withdrawal by the roots; these are saturated moisture content, WCST1-3, field capacity, WCFC1-3, wilting point, WCWP1-3 and WCAD1-3, air dry moisture content. The WCAD is generally considered as 80% of the wilting point. The difference between these two constants is the root water uptake stops below wilting point whereas evaporation from the soil surface continues till the air dry moisture content. These constants primarily depend upon soil texture and organic carbon content, and generally derived through use of pedo-transfer functions. For silty clay loam soils of the test region, the values are given as under:

*WCST1 = 0.55, WCST2 = 0.55, WCST3 = 0.55*
*WCFC1 = 0.35, WCFC2 = 0.35, WCFC3 = 0.35*
*WCWP1 = 0.125, WCWP2 = 0.125, WCWP3 = 0.125*
*WCAD1 = 0.09, WCAD2 = 0.09, WCAD3 = 0.09*

*3.1.18. Irrigation calendar*

Irrigation table, the amount applied in mm and specific day (expressed as days after sowing generally) is indicated as below:

*IRRIG = AFGEN (IRRIGT, DAS)*
*FUNCTION IRRIGT = 0., 0., 19., 0., 20., 60., 21., 0., 44., 0., 45., 0., 46., 0., 84., 0.*

*3.1.19. Rooting depth*

Maximum rooting depth is crop/cultivar/stage specific, in this routine rooting depth of mungbean is simulated. Sub-routine WSRT assesses the moisture condition in the root layer of the growing region for computing the root extension at that time.

*ZRT, rooting depth in mm INTGRL (ZRTI, EZRT)*
*EZRT, rooting depth increment = EZRTC * WSERT * REAAND (ZRTM-ZRT, 1.0-DVS) * INSW (-DVS, 1., 0.)*
*CALL WSRT (ZRT, TKL1, TKL2, TKL3, WCL1, WCL2, WCL3, WCWP1, WCWP2, WCWP3, WSERT), WSRT is a sub-routine to compute water stress effect in layers 1-3 for computing root extension rate*
*EZRTC, potential root extension rate mm/day = 12.*
*ZRTM, maximum possible rooting depth = AMIN1 (ZRTMC, ZRTMS, TKLT)*
*ZRTMS, soil depth criterion for maximum rooting depth, mm = 600.*
*ZRTMC, genetic potential of cultivar for maximum rooting depth, mm = 500.*
*ZRT1 = LIMIT (0., TKL1, ZRT)*
*ZRT2 = LIMIT (0., TKL2, ZRT-TKL1)*
*ZRT3 = LIMIT (0., TKL3, ZRT - TKL1 - TKL2)*
ZRT 1-3 refers to the root thickness, in mm, in layers 1-3 respectively.

In this model, the effect of nitrogen availability and soil edaphic condition has not been taken for evaluating root extension rate.

*3.1.20. Transpiration*

Penman-Monteith method is generally employed for computation of potential evapo-transpiration. On the basis of crop cover function, which is primarily driven by leaf area index, potential transpiration (PTRANS, mm/day) on a given day is computed.

*PTRANS = (1. - EXP (-0.5*LAI))*EVAPR + EVAPD*AMIN1 (2.0, LAI) − 0.5*AINTC*
*FUNCTION EDPTFT = -0.10, 0., -0.05, 0., 0., 0.15, 0 .15, 0.6, 0.3, 0. .3, 0.8, 0.5, 1., 1.1, 1.*

EDPTFT is moisture availability weighted function used for allocating the PTRANS load to various root zone layers

*ERLB = ZRT1*AFGEN (EDPTFT, RWCL1) + ZRT2*AFGEN (EDPTFT, RWCL2) + ZRT3* AFGEN (EDPTFT, RWCL3)*
*TRRM, transpiration load assignment factor to various root zone layers = PTRANS/ERLB*
*TRWL1, water withdrawal from first soil layer mm/day = TRRM*WSE1*ZRT1*AFGEN (EDPTFT, RWCL1)*
*TRWL2, water withdrawal from second soil layer mm/day = TRRM*WSE2*ZRT2*AFGEN (EDPTFT, RWCL2)*
*TRWL3, water withdrawal from third soil layer mm/day = TRRM*WSE3*ZRT3*AFGEN (EDPTFT, RWCL3)*
*ATRANS, actual transpiration rate, mm/day = TRWL1 + TRWL2 + TRWL3*
*TPTRAN, total potential transpiration mm = INTGRL (ZERO, PTRANS)*
*TATRAN, total actual transpiration mm = INTGRL (ZERO, ATRANS)*

For water stress effect on plant processes, in this model we have considered effect on photosynthesis and phenological modifications, and are computed through these parameters:

*PCEW = ATRANS/(PTRANS + 1.E-10)*
*CPEW = AMIN1 (1., 0.5 + ATRANS/(PTRANS + 1.E-10))*

*3.1.21. Evaporation from soil beneath the crop canopy*

Evaporation from the soil beneath the crop canopy is worked out on the basis of radiation reaching the soil surface and moisture available in the root zone layers. The PEVAP, potential soil evaporation is computed on daily basis through the expression as given below:

*PEVAP, potential evaporation rate from soil mm/day = EXP (−0.5*TLAI) * (EVAPR + EVAPD)*

Actual evaporation from soil, on daily basis, is worked through square root of time in days since last wetting through irrigation/rainfall by using the algorithm as given below:

*DSLR, days since last wetting through rain/irrigation = INTGRL (ZERO, TMP8)*
*AEVAP, actual evaporation rate from soil mm/day = INSW (RRAIN-0.5, EVSD, EVSH)*
*TMP8 = INSW (RRAIN - 0.5, 1., - (DSLR -1.)/DELT)*
*EVSH, soil moisture availability driven factor, mm/day = AMIN1 (PEVAP, (WL1 - WCAD1*TKL1)/DELT + WLFL1)*
*EVSD, irrigation/rainfall driven factor, mm/day = AMIN1 (PEVAP, 0.6*PEVAP*(SQRT (DSLR + 1.) − SQRT (DSLR)) + WLFL1)*

Actual evaporation to be allocated to various soil layers, for which weightage function is to be generated through textural dependence and soil moisture availability in respective layers. In general, for coarse textured soils, surface layer contributes to soil evaporation, whereas deeper layers also contribute to evaporation in case of heavier and medium textured soils. This can be set through the value of parameter-EES.

*FEVL1, weightage of layer 1 towards soil evaporation = AMAX1 (WL1 - WCAD1*TKL1, 0.1)*EXP (- EES*(0.25*TKL1))*
*FEVL2, weightage of layer 2 towards soil evaporation = AMAX1 (WL2 - WCAD2*TKL2, 0.1)*EXP (-EES*(TKL1 + (0.25*TKL2)))*
*FEVL3, weightage of layer 3 towards soil evaporation = AMAX1 (WL3 - WCAD3*TKL3, 0.1)*EXP (-EES*(TKL1 + TKL2 + (0.25*TKL3)))*
*EES, soil textural dependent factor = 0.02*
*FEVLT, parameter derived for computation of water withdrawal from various soil layers = FEVL1 + FEVL2 + FEVL3*

Water withdrawal from various soil layers for soil evaporation contribution is thus computed through the algorithm as given below:

*EVSW1, actual soil evaporation contribution from layer 1 = AEVAP*(FEVL1/FEVLT)*
*EVSW2, actual soil evaporation contribution from layer 2 = AEVAP*(FEVL2/FEVLT)*
*EVSW3, actual soil evaporation contribution from layer 3 = AEVAP*(FEVL3/FEVLT)*

Total potential and actual evaporation are computed through the expression as given below:

*TPEVAP, total potential soil evaporation, mm = INTGRL (ZERO, PEVAP)*
*TAEVAP, total actual soil evaporation, mm = INTGRL (ZERO, AEVAP)*

*3.1.22. Nitrogen uptake and nitrogen fixation*

In this model, we have not included N stress effect, but with the help of optimal N-concentration in plant parts and the contribution of *Rhizobium* towards N fixation and subsequent utilization for its uptake by the crop. Uptake of N by plant parts have been computed in the terminal stage.

*NCONCY, nitrogen concentration in seed, fraction on weight basis = 0.035*
*NCONCS, nitrogen concentration in stover, fraction on weight basis = 0.006*
*NCONCBM, nitrogen concentration in total biomass, fraction on weight basis = 0.02*
*NFIXFR, contribution of Rhizobium towards N uptake, fraction on weight basis = 0.67*

*3.1.23. Finish conditions*

In this model, two finish conditions are set for termination of the model.

*FINISH DVS > 2. (development stage at maturity)*
*FINISH DEATH > 0.999 (death = 1. If the crop dies in the initial stages due to water-logging)*
*DEATH = REAAND (0.8 - DVS, WLFL8 - 5.0)*

*3.1.24. Terminal stage*

At terminal stage, uptake of N and contribution of N-fixation through *Rhizobium* is evaluated through the expression as given below:

*TOTNY, N uptake by seeds, kg/ha = WSO*NCONCY*
*TOTNS, N uptake by stover, kg/ha = (TADRW - WSO)*NCONCS*
*TOTNAGBM, N uptake in total above ground biomass, kg/ha = TOTNY + TOTNS*
*TOTNRT, total N uptake by roots, kg/ha = (TDRW - TADRW)*NCONCS*
*TOTNBM, total N uptake by entire biomass, kg/ha = TOTNAGBM + TOTNRT*
*TNFIX, total N fixation through Rhizobium, kg/ha = TOTNBM*NFIXFR*

We can print the outputs on daily time step in the dynamic mode, but for convenience the final values at terminal stage can be written to an external file through use of a sub-routine

*CALL SUBWRI (TIME, WSO, WLV, WST, WRT, TOTNY, TOTNS, TOTNAGBM, TOTNBM, TNFIX)*
*END*
*STOP*

There are few sub-routines, which are written in FORTRAN, are used in this model and have been directly taken from SUCROS2 (van Keulen et al., 1992). These sub-routines are GLA (gain in leaf area index), ASTRO for calculation of astronomical day length, TOTASS for calculation of total gross assimilation and WSRT to decide whether root growth continues or ceases. Inputs needed for running of these sub-routines come from the main module, where specific parameters for soil, crop/cultivar and weather are provided based on the test location/crop.

*3.2. Calibration of the MungGro model*

Model was calibrated for mungbean cultivar BARI Mung-6 for Gazipur growing environment. Test year was 2001 with date of sowing as 83 Julian day and recommended practices were used. Fig. 3 shows the calibration of MungGro results in terms of seed yield. The dataset points were field experiments at multi-location trials of Pulse Research Center, BARI, Bangladesh (BARI, 2011-2017). The simulated results showed overestimation of the model results at lower yield situation, whereas reverse in trend was noticed for higher yield situation. But the performance was satisfactory through higher value of degree of predictability. Moreover, the crop is sensitive to various biotic and abiotic stress conditions, which might not have been possibly included in the running of the model. However the experiments, which were under non limiting condition of abiotic stresses other than water for test cultivar, BARI Mung-6.

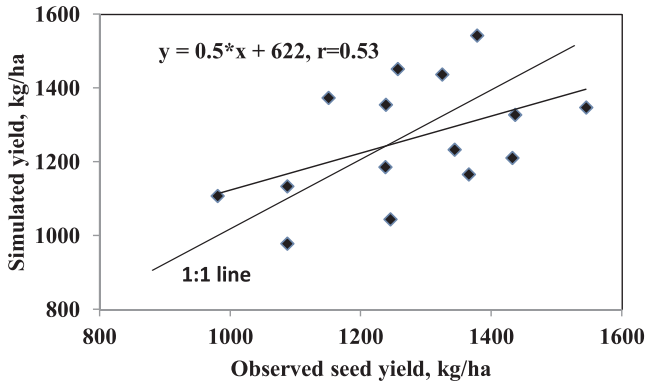


**Fig. 3.** Comparison of observed verses simulated mungbean seed yield by running of MungGro model at multi-location trial results from coordinated Trials of the Pulse Research Center, BARI, Bangladesh.

Fig. 4 shows the performance of the model in terms of total dry matter production. Simulated values were in close agreement with the observed values in the beginning, but the observed values were relatively higher in the later stages of the crop growth. The percent deviation of the simulated values from the observed points ranged from -4.7 to -16.9%. The seed yield till harvest was 1298 kg/ha, whereas the simulated value was 1384 kg/ha, which was 6.6% higher than the observed value. The performance of the model was quite satisfactory.

### 3.3. Validation of mungbean MungGro model

On the basis of annual reports of Pulse Research Center, BARI, Bangladesh. Mung-6 was used as test crop for model run and the simulated values were compared with the observed values (BARI, 2011-2017). The yield had large range of variations as the experiments were compiled over years, indicating the inter-annual climatic variability has significant effect of mungbean seed yield. Trend line was almost in close agreement with the 1:1 line and also the slope of the trend was 1.06, i.e. near to one indicating the perfectness of the model for seed yield estimate (Fig. 5).

### 3.4. Grain yield

Under normal soil moisture condition, grain yield of mungbean reduced greatly because of increase in temperature under same level of $CO_2$ level (Fig. 6). Grain yield reduction because of 1 °C rise temperature is likely to be compensated if $CO_2$ level rise up to 650 ppm. Haque et al. (2005) and Dey et al. (2017) also reported higher grain yields of mungbean with elevated CO2 levels. However, increased $CO_2$ levels are unlikely to compensate yield reduction beyond 1 °C rise. Although there

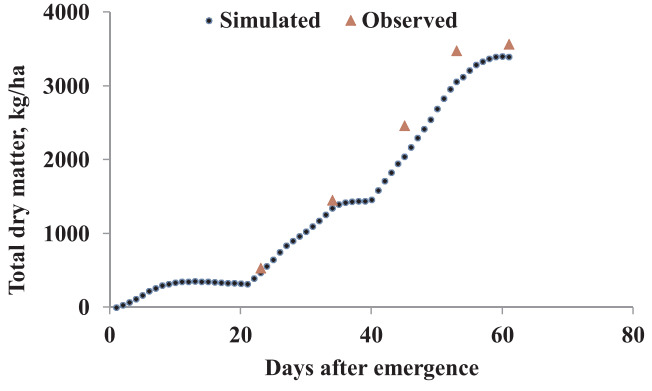


**Fig. 4.** Comparison of simulated verses observed values of temporal course of total dry matter production (kg/ha) of summer mungbean (BARI Mung-6) at Gazipur location.

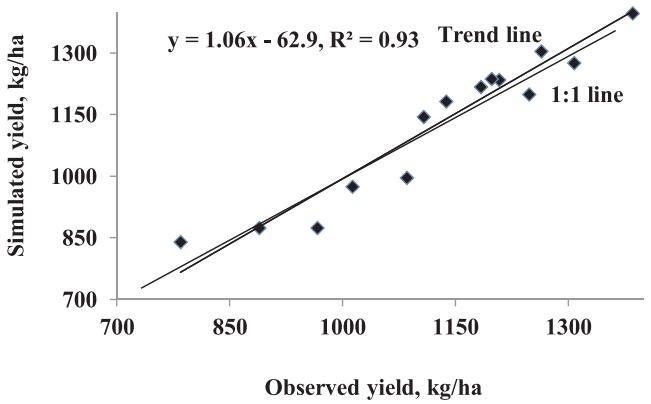


**Fig. 5.** Validation of the mungbean growth model for BARI Mung-6 at Gazipur growing environment.

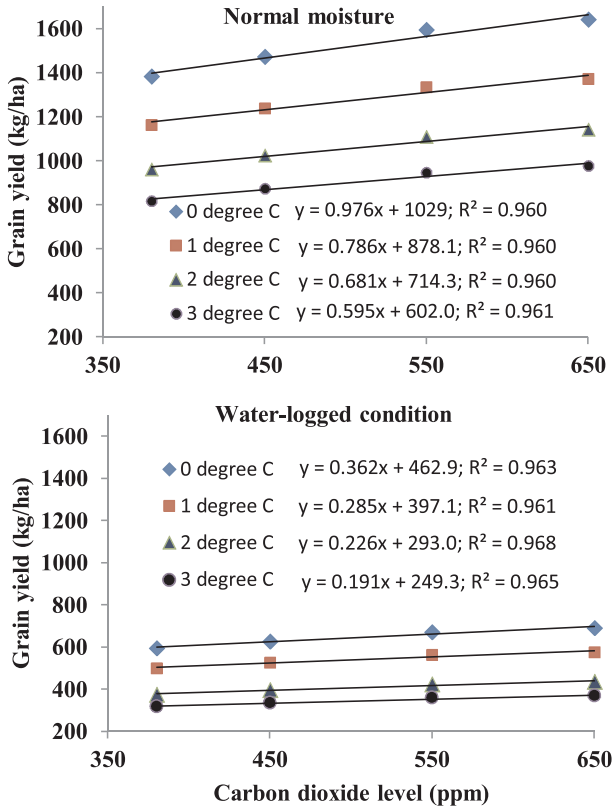


**Fig. 6.** Grain yield of mungbean as influenced by increased temperature, $CO_2$ levels under normal and water-logged (65 and 66 days after sowing) conditions.

is somewhat yield increase with increased $CO_2$ levels, water-logging for two days at 65 and 66 days after sowing severely reduces grain yield of mungbean. Ullah (2006) reported 12–74% yield reduction depending on duration of water-logging.

### 3.5. Crop growth rate

At 380 ppm $CO_2$ level, growth duration reduced by 2.2 days, grain filling duration by 1.2 days and seed weight growth rate by 4.98 kg/ha/day because of each degree rise in temperature (Fig. 7). Haque et al. (2005) and Dey et al. (2017) also reported that higher levels of CO2 reduced pod maturity and increased grain yield. They also reported increased pod numbers and seed size with elevated CO2 levels. Water-logging drastically reduced 1000-grain weight, dry matter production and plant height as reported by Ullah (2006).

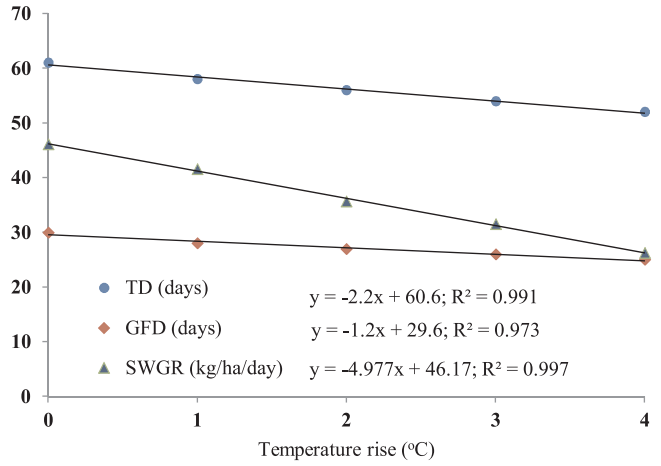


**Fig. 7.** Total growth duration, grain filling duration and seed weight growth rate as influenced by temperature rise at 380 ppm $CO_2$ level.

## 4. Conclusion

Mungbean is an important legume crop in Bangladesh. It is a short duration crop that fit into the major rice based cropping systems and thus provide benefits in terms of soil health and farmer's income. Growth and yield of this crop is highly sensitive to water-logging. In the present study, a mungbean growth model (MungGro) was developed following SUCROS2 model and was written in Fortran Simulation Translator. The G × E interaction coupled with water stress effects was included in this model, and N uptake and N-fixation were simulated at the terminal stage. The model was successfully calibrated and validated for growing environments of Bangladesh. Subsequently the model was tested for temperature and $CO_2$ interactions. Grain yield of mungbean decreased with increasing temperatures which was partially remunerated by increased $CO_2$ levels. The developed MungGro model can be used for studying the climate change impact and natural resource management strategies in south Asian growing regions for this important crop.

## Acknowledgements

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